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Deglaciation chronology of the Donegal Ice Centre, northwest Ireland

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ABSTRACT:

During the Last Glacial Maximum, Donegal in NW Ireland functioned as an independent centre of ice dispersal that separated and fed into the Donegal Bay Ice Stream (sourced in the Irish Midlands) to the south and the Hebrides/Malin Sea Ice Stream to the north. We report geochronological data that demonstrate marked contrasts in the timing and rate of deglaciation in northern and southern Donegal. In northern Donegal, which occupied an inter-ice-stream location, decoupling from the Hebrides/Malin Sea Ice Stream resulted in formation of a marine embayment along the north coast by ~22–21 ka, and subsequent slow (~4±1 m a^{-1}) climatically-driven inland retreat of the ice margin to mountain source areas by ~17 ka. By contrast in southern Donegal, which lay near the axis of the Donegal Bay Ice Stream, deglaciation was delayed until ~18 ka following readvance of ice to a moraine in outer Donegal Bay. The ice margin subsequently underwent net retreat, apparently uninterrupted by readvances, at a net rate of ~ 18±6 m a^{-1}. A mean terrestrial cosmogenic nuclide age of ~14.8 ka obtained for samples from the foothills of the Blue Stack Mountains in SE Donegal indicates that ice persisted in valley heads and cirques at the beginning of the Lateglacial Interstadial, suggesting that these and nearby mountains supported the last remnants of the Irish Ice Sheet prior to complete deglaciation of Ireland, and that almost all of the shrinkage of the ice sheet in this sector occurred under stadial conditions prior to the onset of interstadial warming at ~14.7 ka.

KEYWORDS: British-Irish Ice Sheet, deglaciation, terrestrial cosmogenic nuclide surface exposure dating, northwest Ireland

Introduction

During the last (Late Devensian / Late Midlandian) ice-sheet glaciation of Britain and Ireland, (~32–15 ka) the mountains of Donegal in northwest Ireland formed an independent centre of ice dispersal within the more extensive British-Irish Ice Sheet (BIIS). Ice radiating from the Donegal Ice Centre fed north and northwest into a major ice stream (the Hebrides/Malin Sea Ice Stream) on the adjacent Malin Shelf, west and southwest into Donegal Bay, and to the east was confluent with the ice occupying the Irish Midlands. The Donegal ice dome was therefore pivotal in separating ice flows from the Irish Midlands and western Scotland (Fig. 1). Radial ice flow over Donegal for at least part of the last glaciation is demonstrated by the distribution of local erratics, absence of allochthonous erratics, and the alignments of drumlins, moraines, roches moutonnées, striae and meltwater channels (Charlesworth, 1924; Dury, 1957, 1958, 1964; Stephens and Synge, 1965; Colhoun, 1973; McCabe *et al*., 1993; Knight and McCabe, 1997; Ballantyne *et al*., 2007; Smith and Knight, 2011; Knight, 2012). Flowsets reconstructed by Greenwood and Clark (2009b) show that ice moving south from the Donegal Ice Centre was confluent with west-flowing ice from the Irish Midlands in Donegal Bay, forming an ice stream (the Donegal Bay Ice Stream) that extended northwestwards towards the shelf edge.

Geophysical data obtained for the adjacent offshore shelves indicate that at the global Last Glacial Maximum (gLGM; 26.5-19 ka, P.U. Clark *et al*., 2009)) grounded ice extended as far as the shelf break, ~100 km to the west, where it terminated in a marine setting (Benetti *et al*., 2010; Dunlop *et al*. 2010; Ó Cofaigh *et al*., 2012). These data also indicate that Donegal ice coalesced with ice from western Scotland ~60 km north of the present Donegal coastline. Donegal is therefore the key location for determining the timing of decoupling of Irish- and Scottish-sourced ice during the last deglaciation, and is also important for establishing the chronology of ice retreat after the ice margin had retreated to the present coastline.

As part of the wider BRITICE-CHRONO project (http://www.sheffield.ac.uk/geography/research/britice-chrono/home), designed to establish a detailed deglaciation chronology of the last BIIS, we present 20 new ^{10}Be and ^{36}Cl terrestrial cosmogenic nuclide (TCN) surface exposure ages from six sites in Donegal that were selected to complement and extend the existing deglaciation chronology. The aims of this paper are: (1) to establish the timing of the decoupling of Scottish and Irish ice flowing west across the Malin Shelf; (2) to reconstruct the chronology of ice margin retreat in Donegal Bay; (3) to determine the net rate of ice-margin recession inland from the north coast of Donegal and in Donegal Bay; (4) to establish for how long ice persisted locally in the Donegal mountains following its retreat from coastal lowlands; and (5) to explore the wider implications of our results for the interpretation of the deglaciation chronology of the western sector of the last BIIS. The chronology of offshore ice margin retreat from the shelf edge towards the present coastline is considered in a separate paper based on new radiocarbon ages obtained from marine microfauna retrieved from sediment cores along a transect from the shelf edge to the outer part of Donegal Bay (Ó Cofaigh *et al*., 2018).

Donegal

Regional setting and ice dome extent

County Donegal (54º28'–55º22' N, 06º55'–08º46' W) is predominantly underlain by granites, quartzites and schists with a pronounced northeast-southwest structural grain that has been accentuated by repeated episodes of Quaternary glacial erosion (Long and McConnell, 1997, 1999). The north and west of the county are mountainous; many summits exceed 500 m OD with the highest point (Errigal) at 751 m OD. From detailed mapping of erosional and depositional landforms, Charlesworth (1924) proposed that the Donegal mountains had nourished and maintained an independent ice dome during the last glaciation, and placed the former ice divide along a line running approximately north-south from the Derryveagh Mountains to the Blue Stack Mountains, close to the present watershed (Fig. 1). He showed that ice-flow from this elongated dome was essentially radial with a focus along pre-existing structurally-controlled valleys, but argued that during maximum ice extent topography was probably less of a constraining influence on ice-flow directions than during build-up and retreat phases. Subsequent work is generally supportive of this ice dome hypothesis (e.g. Ballantyne *et al*., 2007; Greenwood and Clark, 2009; Smith and Knight, 2011).

In contrast, the thickness attained by the ice dome has been a contentious issue. Charlesworth (1924) claimed that all summits lay beneath the ice, although it is not clear if he was referring to the local Last Glacial Maximum (lLGM), which is placed at ~26.3–24.8 ka at the shelf break to the west of Donegal (Ó Cofaigh *et al*., 2018). Complete burial of the mountains by the last ice sheet was favoured by McCabe (1995), while Sellier (1995) maintained that areas above ~550 m OD in the Derryveagh Mountains had remained ice free. On the basis of geomorphological evidence and clay-fraction mineralogy, Ballantyne *et al*. (2007) argued for an ice-shed altitude in excess of 700 m OD, but also reported an absence of evidence for glacial modification on six peripheral summits, including Errigal, and regarded these as being either nunataks during the lLGM or buried beneath a cover of non-erosive cold-based ice.

Conflicting interpretations also concern the lateral extent of the Donegal ice dome. Although Charlesworth (1924) envisaged ice extending offshore to the north and west, others have placed the limit onshore in the north of the county (Stephens and Synge, 1965; Bowen *et al*., 2002), and a limited offshore extent of ~10-30 km to the west has been suggested (e.g. McCabe, 1985;

Bowen *et al*., 1986; Knight, 2003; Ballantyne *et al*., 2007). More recent work utilising geophysical techniques to image seabed topography has demonstrated that a concentric sequence of nested moraine ridges indicative of deposition by a grounded ice mass extends westwards to the shelf break 90–100 km from the west coast of Donegal (Sejrup *et al*., 2005; Benetti *et al*., 2010; Dunlop *et al*. 2010; Ó Cofaigh *et al*., 2012). Radiocarbon dates obtained for marine microfauna in cores retrieved from sediments on the Atlantic shelf northwest of Ireland confirm that these moraines were deposited at the margin of the last ice sheet, and indicate that ice nourished in Donegal began to retreat from the shelf edge in the interval between 26.3 and 24.8 ka cal BP (Ó Cofaigh *et al.* 2018).

Recognition that the last ice sheet extended to the edge of the Malin Shelf strongly suggests that the Donegal ice dome was of sufficient thickness to have buried all mountain summits during the lLGM, a proposition also supported by climate-proxy-driven thermo-mechanical models of ice-sheet build-up and decay (Hubbard *et al.,* 2009). Support for this premise comes from southwest Ireland where Ballantyne *et al*. (2011) have argued that the Kerry-Cork Ice Cap attained an altitude of at least 1200 m OD, >200 m above the highest summits, and from northwest Scotland where Fabel *et al*. (2012) have demonstrated that the last ice sheet overtopped all mountain summits. It is therefore extremely unlikely that any of the mountain summits in Donegal formed palaeonunataks during the lLGM (Ballantyne and Ó Cofaigh, 2017).

Legacy ages, related BRITICE-CHRONO ages and deglaciation

Several previous studies have utilised either TCN (cosmogenic ^{10}Be or ^{36}Cl) surface exposure dating or ^{14}C dating to establish the timing of ice retreat and/or readvance from sites in Donegal. Collectively these ages provide the foundation of a deglaciation chronology (Fig.1; Table 1).

Cosmogenic ^{10}Be exposure ages cited here have been recalibrated using the Loch Lomond Production Rate (LLPR), and are followed in brackets by the equivalent ages obtained from the CRONUScalc online calculator; details of these procedures are given in the next section. The ^{14}C ages have been (re)calibrated using OxCal 4.2 and, for marine-derived samples, the Marine-13 dataset with a marine reservoir correction of 400 years (Bronk Ramsey, 2009; Reimer *et al.,* 2013). All ^{14}C ages are reported to two decimal places as cal ka BP; TCN ages are reported to one decimal place as ka. Mean ages reported for two or more TCN ages below and in Tables 1 and 3 are uncertainty-weighted means.

Bowen *et al*. (2002) obtained ^{36}Cl ages of 25.1±1.1 ka, from glacially-smoothed quartzite bedrock at Malin Head, and 31.0±17.0 ka, from either a glacially-transported granite boulder or bedrock at Bloody Foreland, but the large uncertainty on the latter age prevents meaningful interpretation, and the former is probably compromised by nuclide inheritance (Ballantyne and Ó Cofaigh, 2017). For Corvish, at the head of Trawbreaga Bay on the north coast, McCabe and Clark (2003) reported ^{14}C ages for marine microfaunas within *in-situ* and deformed marine sediments. The basal *in-situ* laminated muds yielded ages of 20.68±0.16 cal ka BP and 18.24±0.13 cal ka BP; the older date implies initial deglaciation before ~20.7 cal ka BP. Overlying deformed sands and muds gave ages of 19.50±0.50, 18.32±0.18 and 19.03±0.19 cal ka BP, and were interpreted by McCabe and Clark (2003) as evidence for reworking of the underlying laminated muds by ice readvance at ~18 ka. An age of 17.06±0.18 cal. ka BP from *in-situ* rhythmically bedded marine muds overlying the deformed muds was regarded as minimal for final deglaciation of the bay.

Seven consistent ^{10}Be exposure ages from glacially-transported boulders on a lateral moraine at Bloody Foreland, the northwesternmost point of Donegal, have given an uncertainty-weighted mean age of 21.8±1.2 ka (21.1±1.8 ka) (Ballantyne *et al*., 2007; Clark *et al*., 2009a; Ballantyne and Ó Cofaigh, 2017; Fig. 2a). Two ^{10}Be exposure ages from bedrock and a glacially-transported boulder on Aran Island, 20 km southwest of Bloody Foreland, have yielded an uncertainty-weighted mean age of 21.7±1.1 ka (21.0±1.7 ka) (Cullen, 2013). The consistency of these two mean ages provides strong support for retreat of the ice-sheet margin across the Irish sector of the Malin Shelf between ~26–25 ka and ~22–21 ka (Clark *et al*., 2012; Ó Cofaigh *et al*., 2012, 2018), decoupling of Malin Shelf ice from Donegal Bay ice at ~22–21 ka and the beginning of ice retreat at that time from the present coast towards the mountains. At Glencolumbkille in southwest Donegal, ^{10}Be exposure ages of 17.9±0.9 ka (17.4±1.4 ka) and 19.8±1.0 ka (19.1±1.5 ka) from vein quartz in, respectively, a glacially-transported boulder and a roche moutonnée were reported by Ballantyne *et al.* (2007). The latter age overlaps within 1σ uncertainties with the mean values from Bloody Foreland and Aran Island, but may be compromised by nuclide inheritance (see below).

The timing of deglaciation of the mountains of Donegal is indicated by ^{10}Be exposure ages for two sites. Glacially-plucked bedrock at 405–430 m OD on a col to the east of Errigal in north Donegal has produced three consistent ^{10}Be exposure ages averaging 17.8±0.9 ka (17.6±1.4 ka) and a minimum age for deglaciation of Slieve League in southwest Donegal is provided by three consistent ^{10}Be exposure ages averaging 17.1±0.9 ka (16.9±1.4 ka) obtained for samples from rockslide runout debris (Ballantyne *et al*., 2013b).

A ^{14}C age of 15.38±0.12 cal ka BP from the basal organic mud of Lough Nadourcan (Watson *et al*., 2010) provides a minimum age for deglaciation of the low ground along the eastern margin of the Derryveagh Mountains. However, this age is ~700 years earlier than the rapid warming identified in the Greenland ice core records and INTIMATE event stratigraphy as marking the onset of the Lateglacial Interstadial at ~14.7 ka (Rasmussen *et al*., 2014), suggesting that the Lough Nadourcan basal ^{14}C age may be compromised by the incorporation of reworked older carbon. Nevertheless, it is unlikely that ice on low ground survived much beyond the start of interstadial warming even if small glaciers persisted in the mountains.

Legacy ages from sites in north Mayo, along the south side of Donegal Bay, and BRITICE-CHRONO ages from Donegal Bay (Fig. 1) are relevant to the deglaciation chronology of south Donegal, and therefore are also considered here. McCabe *et al*. (1986, 2005) reported eight ^{14}C ages obtained for marine shells and foraminifera within glacimarine sediments at Fiddauntawnanoneen and Belderg Pier on the north coast of Mayo. Seven of these ages range between 20.38±0.31 cal ka BP and 19.16±0.21 cal ka BP; the remaining age (22.09±0.28 cal. ka BP) is significantly older and may indicate the reworking of older sediment (J. Clark *et al*., 2012). Deglaciation of these adjacent sites and, by inference, the outer reaches of Donegal Bay, therefore appears to have occurred around or slightly before ~20 ka (Ballantyne and Ó Cofaigh, 2017).

To the northeast of these two sites, a distinct ice margin position is represented by the Donegal Bay Moraine (DBM), an offshore moraine that extends for 35 km north-south across outer Donegal Bay (Benetti *et al.,* 2010; Ó Cofaigh *et al.* 2012). Deformation of stratified glacimarine deposits indicates that the moraine represents a readvance of the ice margin. Radiocarbon ages for mixed benthic foraminifera within glacimarine sediments in 76–99 m water depth on either side of the moraine (Fig. 1) constrain moraine formation to between 20.24±0.24 cal ka BP and 17.92±0.16 cal ka BP (Ó Cofaigh *et al*., 2018), and moraine formation at 20–19 ka was inferred by Ó Cofaigh *et al*. (2018).

Finally, eight cosmogenic ^{10}Be exposure ages from vein quartz in glacially-transported boulders at three sites associated with the Tawnywaddyduff moraine system on the northern slopes of the Ox Mountains south of Sligo Bay (Fig. 1) returned ages ranging from 21.1±1.7 ka (21.0±2.3 ka) to 15.7±1.6 ka (16.0±2.0 ka). The overall average of these ages (~18 ka) was taken by Clark *et al*. (2009b) to represent the timing of a readvance of the ice sheet and construction of the moraine.

However, Ballantyne and Ó Cofaigh (2017) questioned this conclusion, noting that the age range spanned >5 ka and that two distinct age groupings are represented, with three older ages (mean 20.3±1.3 ka (20.3±1.9 ka)) and five younger ages (mean 16.6±1.0 ka (16.7±1.5 ka)). The older sample ages are from a site on the west side of the Ox Mountains; four of the younger ages are from the east side and the other age came from the northern slopes.

Field sites and methods

The six sites sampled for TCN surface exposure dating were selected to provide deglaciation-age transects along the north and south coasts of Donegal and an additional deglaciation age for the northern (Derryveagh) mountains (Fig. 1). For the north coast transect we sampled on the headlands of Rosguill and Malin Head, respectively 29 km and 63 km northeast of the Bloody Foreland site dated by Ballantyne *et al*. (2007) and Clark *et al*. (2009a). For the southern transect we sampled at Glencolumbkille, close to the western extremity of the Slieve League peninsula, at Kilcar on the SW coast of Donegal, and on the lower southern slopes of the Blue Stack Mountains. The latter two sites are, respectively, 14 km southeast and 41 km east of Glencolumbkille. In the northern mountains we obtained samples from a prominent valley-floor boulder limit in the Poisoned Glen, Derryveagh Mountains.

Samples were collected from the upper surface of large, glacially-deposited boulders or ice-scoured bedrock using a hammer and chisel. Twelve boulder samples comprised whole rock (granite, conglomerate sandstone or dolerite), four were from protruding quartz veins in quartzite or schist boulders, two consisted of quartz pebbles embedded in conglomerate boulders, and two samples were from quartzite bedrock (Fig. 2, Table 2). A compass and clinometer were used to record the geometry of the sampled surfaces and the skyline topography. Locations and altitudes were determined with a hand-held GPS unit cross-referenced to a 1:50,000 topographic map. Sample thickness was measured using callipers, density was determined by the displacement of sub-samples in water, and topographic shielding was calculated using the CRONUS-Earth online calculator (Table 2).

Samples were processed for cosmogenic ^{10}Be and ^{36}Cl analysis at the NERC Cosmogenic Isotope Analysis Facility (CIAF). For ^{10}Be, samples were crushed and sieved to 250-500 µm and quartz was separated in a Frantz® isodynamic magnetic mineral separator. before being repeatedly etched with HF (Kohl and Nishiizumi, 1992). Purified quartz was spiked with ~0.2 mg of ^{9}Be and dissolved. Be was extracted and isolated following the methodology described in Child *et al*. (2000) before being, precipitated as $Be(OH)_2$ and baked to BeO in a quartz crucible. BeO was mixed with Nb and pressed into a copper cathode. For ^{36}Cl, samples were crushed and sieved to <500 µm, leached in hot HNO_3 (trace metal analysis grade) and then washed thoroughly with ultrapure water to remove meteoric ^{36}Cl contamination from grain surfaces. Each sample was then split into two fractions: about 2 g for elemental analysis by ICP-OES and ICP-MS, and about 20 g for analysis of ^{36}Cl by accelerator mass spectrometry (AMS). Chlorine was extracted and purified from the 125–250 µm fraction of leached samples and precipitated as AgCl using modified version of procedures developed by Stone *et al*. (1996). Samples were processed together with a full chemistry blanks.

$^{10}Be/^{9}Be$, $^{36}Cl/^{35}Cl$ and $^{36}Cl/^{37}Cl$ ratios were measured using the 5MW pelletron at SUERC (Xu *et al*., 2010, Wilcken *et al.* 2013) and normalised to NIST SRM4325 with a $^{10}Be/^{9}Be$ ratio of 2.79×10^{-11} (Nishiizumi *et al*., 2007), and Z93-0005 (PRIME Lab, Purdue) with a $^{36}Cl/Cl$ ratio of 1.2×10^{-12}. Cosmogenic nuclide concentrations include a blank correction of 3-14% for ^{10}Be and 1-5% for ^{36}Cl (Table 3). The uncertainties in the cosmogenic nuclide concentrations include the AMS counting statistics and scatter uncertainties from sample, procedural blank, and standards measurements.

Age calculation and filtering

The cosmogenic ^{10}Be ages were calculated using two methods. First, ages were determined using version 2.3 of the online calculators formerly known as CRONUS-Earth ^{10}Be-^{26}Al exposure age calculators (Balco *et al.,* 2008: http://hess.ess.washington.edu/math/al_bev_23/al_be_multiple v23.php) using the independently-constrained Loch Lomond production rate (LLPR; nominal production rate 4.00±0.18 atoms g^{-1} a^{-1}; Fabel *et al*., 2012), the default production rate employed in the BRITICE-CHRONO dating programme. Exposure ages were based on the time-dependent Lm scaling (Lal, 1991; Stone, 2000) and assume 1 mm ka^{-1} of post-depositional surface erosion (cf. André, 2002; Nicholson, 2009; Larsen *et al*., 2012).

We also calculated cosmogenic ^{10}Be exposure ages using the CRONUScalc program version 2.0 (Marrero *et al*., 2016a) and the default global production rate of 3.92 atoms g^{-1} a^{-1} for Lm scaling (Borchers *et al*., 2016), again assuming an erosion rate of 1 mm ka^{-1}. Both production rates agree within ±1σ uncertainties with the range of production rates determined for other high latitude sites in the northern hemisphere (Phillips *et al*., 2016).

^{36}Cl ages are presented as determined using the CRONUScalc calculator which uses production rates of 56±4.1 at ^{36}Cl (g Ca)$^{-1}$ a^{-1} for Ca spallation, 155±11 at ^{36}Cl (g K)$^{-1}$ yr^{-1} for K spallation and 759±180 neutrons (g air)$^{-1}$ a^{-1} (Marrero *et al*., 2016b). Table 3 presents the ^{10}Be and ^{36}Cl data and exposure ages with associated uncertainties for both methods of calculation.

Within-site consistency of ages was tested using the reduced Chi-square statistic (χ^2_R) (Bevington and Robinson, 2003). Where the χ^2_R value for a sample of ages from a single site exceeds the critical value at the 95% level, it was inferred that geological uncertainty contributed to the observed age scatter. In such cases outlier ages were manually removed until a χ^2_R value less than the critical value was obtained; the remaining ages were regarded as consistent with and representative of a single age population, with age scatter being due to measurement error alone (Balco, 2011; Applegate *et al*., 2012; Small and Fabel, 2016; Small *et al*., 2017a). For sites having two or more internally consistent ages the uncertainty-weighted mean was determined and is regarded as providing the best estimate exposure age for the site. As with the legacy TCN ages discussed above, we cite the ^{10}Be weighted mean ages determined with the LLPR first, followed by the equivalent ages calculated with CRONUScalc in brackets.

Results

The 20 new TCN surface exposure ages and uncertainty-weighted mean values for internally consistent ages for each site are given in Table 3 and Fig. 3. These ages are assessed below in relation to published ages for the region (Table 1).

The ages for Rosguill and Malin Head, on the north coast of Donegal, complement published deglacial age estimates for the northern sites of Aran Island, Bloody Foreland and Corvish. A mean value was not calculated for Malin Head because the three samples failed to yield an acceptable χ^2_R value, due to their wide age scatter (~25.5–20.7 ka and 25.2–20.2 ka). However, sample MH-03 yielded an age of 20.7±1.2 ka (20.2±1.7 ka), reasonably consistent with the TCN mean ages of 21.7±1.1 ka (21.0±1.7 ka) for Aran Island, 21.8±1.2 ka (21.1±1.8 ka) for Bloody Foreland, and the mean age of 18.8±0.9 ka (18.6±1.5 ka) for Rosguill; in addition, the MH-03 age is consistent with the minimum deglaciation ^{14}C age of 20.68±0.16 cal ka BP for Corvish, and it therefore provides the best fit age of the three Malin Head ages. Furthermore, Malin Head is the most easterly of our sites and is unlikely to have been deglaciated before the more westerly sites. The other two Malin Head samples are considered to be compromised by nuclide inheritance.

The mean age of 16.7±0.9 ka (16.2±1.4 ka) for the Poisoned Glen boulder limit in north Donegal is statistically indistinguishable from the mean age of 17.8±0.9 ka (17.6±1.4 ka) obtained from ice-plucked bedrock on Errigal, 2.2 km north and 350 m higher. Together these two sites indicate that the northern mountains were largely deglaciated by ~18-17 ka.

In south Donegal, the consistent exposure ages obtained from three boulders from Glencolumbkille yield a mean age of 16.7±0.8 ka (16.4±1.4 ka). Two legacy samples from this location had returned ages of 17.9±0.9 ka (17.4±1.4 ka) and 19.8±1.0 ka (19.1±1.5 ka). The former age is statistically indistinguishable from the three new ages, and collectively all four ages produce an uncertainty weighted mean age of 17.2±0.8 ka (16.8±1.3 ka) (χ^2_R = 1.75 and 1.64 respectively). The latter age possibly reflects the influence of nuclide inheritance. The Glencolumbkille ages are also consistent with three legacy samples from rockslide runout debris on Slieve League (7 km SE of Glencolumbkille) that yielded a mean minimum age for deglaciation of 17.1±0.9 ka (16.9±1.4 ka).

Four samples from dolerite boulders at Kilcar gave ^{36}Cl exposure ages ranging from 18.1±1.7 ka to 42.0±6.0 ka. Samples KC-02, -03 and -04 returned ages that pre-date the LGM and are probably compromised by nuclide inheritance. The other sample (KC-01: 18.1±1.7 ka) is consistent with the wider geochronological evidence for the timing of deglaciation in south Donegal and north Mayo.

The four samples obtained from boulders on low ground (~150 m) at the foot of the Blue Stack Mountains yielded consistent (χ^2_R <1.0) ages ranging from 15.6±0.9 ka (15.6±1.4 ka) to 14.4±0.8 ka (14.5±1.3 ka), and an uncertainty-weighted mean age of 14.8±0.7 ka (14.8±1.2 ka). These results imply deglaciation of all low ground at the head of Donegal Bay before ~14.7 ka.

They also suggest that ice persisted much later in the Blue Stack Mountains than in the Derryveagh Mountains of northern Donegal, where the available dating evidence suggests deglaciation of the Errigal col at ~17.8 ka and ice withdrawal from the Poisoned Glen boulder limit at ~16.7 ka.

Discussion

In conjunction with the published legacy ages discussed earlier, the new ages presented here provide spatially-consistent constraints on the timing of deglaciation in Donegal (Fig. 3). Below we discuss deglaciation of northern and southern Donegal separately, because during the lLGM northern ice fed the Hebrides/Malin Sea Ice Stream that drained ice from western Scotland across the Malin Shelf, whereas southern ice contributed to the Donegal Bay Ice Stream that drained ice from the Irish Midlands to the shelf edge through Donegal Bay.

Deglacial chronology of north Donegal

The TCN ages relating to deglaciation of Aran Island (mean = 21.7±1.1 ka (21.0±1.7 ka)), Bloody Foreland (mean = 21.8±1.2 ka (21.1±1.8 ka)), and Malin Head (a single TCN age of 20.7±1.2 ka (20.2±1.7 ka)), together with the oldest ^{14}C age from Corvish (20.68±0.16 cal ka BP) indicate progressive eastward retreat of the ice margin along the northern coast of Donegal between ~21.8 ka and ~20.7 ka. The Bloody Foreland and Aran Island ages imply that decoupling of ice sourced in Donegal from the Scottish-sourced Hebridean Ice Stream commenced within the interval ~22–21 ka; this is slightly earlier than previous estimates, which have placed initial disengagement of these two ice masses after ~21 ka (Small *et al.,* 2017). The single Malin Head TCN age and the oldest ^{14}C age at Corvish indicate that separation of Scottish-sourced ice and Donegal-sourced ice was complete by ~20.7 ka, implying that by this time a marine embayment extended eastward along the north coast of Donegal, separating ice flowing north and northeast from the Donegal Ice Centre from the retreating Hebrides/Malin Sea Ice Stream.

The timing of ice retreat inland towards the Derryveagh Mountains of northern Donegal is provided by the TCN ages obtained for the two sites in the heart of this range, at ~420 m OD on Errigal col (mean = 17.8±0.9 ka (17.6±1.4 ka)) and, 2.2 km to the south, a low-level site (~74 m OD) at the mouth of the Poisoned Glen (mean = 16.7±0.9 ka (16.2±1.4 ka)). Although these two ages are statistically indistinguishable within uncertainties (Fig. 4), the difference between them may imply exposure of Errigal col by downwasting ice several centuries prior to retreat of ice in the Poisoned Glen. Irrespective of whether or not this was the case, the deglaciation ages for both sites imply that ~3000–5000 years elapsed between deglaciation of Aran Island and Bloody Foreland and deglaciation of the Derryveagh Mountains (Fig. 3). A further implication is that net ice margin retreat rates were extremely slow. The Errigal col and Poisoned Glen sites lie respectively 15 km and 17 km SE of the Bloody Foreland site; if the mean deglaciation ages for these sites are representative, then the net ice-margin retreat rate from Bloody Foreland to both sites was ~4 m a^{-1}; taking the associated uncertainties into account suggests that net retreat rate is unlikely to have exceeded 5 m a^{-1}, and may have been as low as 3 m a^{-1}. By contrast, assuming that the ice margin began to retreat from the shelf edge within the interval 26.3 ka to 24.8 ka (Ó Cofaigh *et al.*, 2018), the implied net rate of offshore ice-margin retreat from the shelf break to Bloody Foreland falls within the range ~19.2–33.3 m a^{-1}. Ó Cofaigh *et al.* (2018) inferred that ice-sheet retreat from the shelf edge was initiated by calving associated with high sea levels induced by glacio-isostatic depression rather than changing climate, and the marked slowing of retreat after the ice margin had become land-based in northern Donegal appears consistent with this interpretation: the inferred slow net retreat rates of Donegal ice in this sector over the period ~21 ka to ~17 ka suggest that the retreating ice was close to equilibrium with prevailing climate, and experienced only a slight net negative mass balance during this period.

Averaged net retreat rates, however, may obscure oscillations of the ice margin, with periods of retreat alternating with limited readvances. At present there is dated stratigraphic evidence for only one such readvance, at Corvish, near the head of Trawbreaga Bay (Fig. 3). Readvance occurred over a distance of at least 5 km according to McCabe and Clark (2003). At this site, the youngest radiocarbon age obtained for *Elphidium clavatum* tests in deformed marine silts (18.32±0.18 cal ka BP) and a single age for *E.clavatum* tests in overlying undeformed silts (17.06±0.18 cal ka BP) have been interpreted by McCabe and Clark (2003) as bracketing the timing of readvance of the ice margin on the northern coast of Donegal. They placed the timing of this readvance at ~18 ka, though the dating evidence appears consistent with readvance of the ice margin at any time within the interval ~18.5–16.9 ka. On the assumption that the Corvish readvance occurred at ~18 ka, McCabe *et al.* (2007) suggested that it correlates with the Clogher Head Readvance (CHR) in NE Ireland, though reinterpretation of the stratigraphic and dating evidence indicates that the CHR was a short-lived event that peaked rather earlier, at ~18.4 ka (Ballantyne and Ó Cofaigh, 2017). Thus although the two readvances may be coeval and represent a regional-scale event that occurred in response to climatic forcing (McCabe *et al*., 2007; J. Clark *et al*., 2012) it is equally feasible that they occurred at different times and represent localised oscillations of the ice margin (C.D. Clark *et al*., 2012). The TCN mean age of 18.8±0.9 ka (18.6±1.5) indicative of the timing of deglaciation at Rosguill predates the bracketing ages for the readvance at Corvish (~18.5–16.9 ka), but because of the uncertainties associated with the TCN age we cannot not preclude the possibility that the Rosguill site was reoccupied by glacier ice during the same readvance event.

The TCN mean age for the Poisoned Glen (16.7±0.9 ka (16.2±1.4 ka) implies that ice persisted in the Derryveagh Mountains until ~17–16 ka, but the ^{14}C age of 15.38±0.12 cal. ka BP from Lough Nadourcan (Watson *et al.,* 2010) suggests that ice had disappeared from low ground surrounding these mountains before the rapid warming associated with the onset of the Lateglacial Interstadial at ~14.7 ka. Valley heads, cirques and plateaus in the Derryveagh Mountains may, however, have retained ice until early in the interstadial, as appears to have been the case for the Blue Stack Mountains of south Donegal (see below).

Deglacial chronology of south Donegal and Donegal Bay

As noted earlier, the Donegal Bay Moraine (DBM) that crosses outer Donegal Bay (Fig. 3) represents the limit of a readvance of ice fed from Donegal Bay. Radiocarbon ages of 20.24±0.24 cal ka BP and 17.92±0.16 cal ka BP obtained for foraminifera retrieved respectively from the distal and proximal sides of the moraine constrain its age (Ó Cofaigh *et al.,* 2018). This broad interval encompasses the timing of both the readvance at Corvish in northern Donegal and that of the Clogher Head Readvance in NE Ireland (McCabe and Clark, 2003; McCabe *et al.,* 2007; J. Clark *et al.,* 2012; Ballantyne and O Cofaigh, 2017), but the resolution of the dating evidence is inadequate to establish contemporaneity. The position and alignment of the DBM suggests that the sites at Belderg Pier and Fiddauntawnoneen on the south coast of outer Donegal Bay lay outside the readvance, and the radiocarbon ages of ~20–19 cal ka BP obtained by McCabe *et al.* (1986, 2005) for *in situ* marine fauna within glacimarine sediments at these sites (Table 1) are consistent with this interpretation (Fig. 3). Conversely the aggregated TCN mean age for Glencolumbkille in SE Donegal (17.2±0.8 ka (16.8±1.3 ka)), the single TCN age for Kilcar (18.1±1.7 ka), and the minimum deglaciation age represented by postglacial rockslide debris at nearby Slieve League (17.1±0.9 ka (16.9±1.4 ka)) suggest that southern Donegal lay within the limits of the readvance that produced the DBM. Similarly, the five 'younger' TCN ages (mean = 16.6±0.1.0 ka (16.7±1.5 ka)) reported by Clark *et al.* (2009) for the Twanywaddyduff moraine system of the northern Ox Mountains (Fig. 3; Table 1) indicate persistence of ice cover along the inner part of Donegal Bay after ~17 ka. Collectively, these two sets of ages suggest that much or all of Donegal Bay continued to support ice cover as late as ~17 ka, though it is possible that a calving margin along the axis of the bay led to development of an ice-free marine corridor between its northern and southern shores.

The TCN mean age of 14.8±0.7 ka (14.8±1.2 ka) from the southern flanks of the Blue Stack Mountains suggests that Donegal Bay had become ice free by ~15 ka but that ice still occupied mountain valleys and cirques near the head of the bay (Fig. 3). The implication of this age is that mountain ice probably persisted for some time following the onset of the Lateglacial Interstadial at ~14.7 ka. The Blue Stack ages are the youngest ages for deglaciation hitherto reported for Ireland (*cf.* Ballantyne and Ó Cofaigh, 2017), suggesting that these and possibly other mountains in NW Ireland supported the last remnants of the last Irish Ice Sheet prior to complete disappearance of glacier ice under the warmer conditions of the Lateglacial Interstadial.

The sampling sites at Glencolumbkille and the Blue Stack Mountains are separated by a distance of 41 km. The mean TCN ages for these two sites imply that net ice margin retreat between these two sites occurred over ~2,200 years, implying a net retreat rate of ~19 m yr^{-1}; taking the associated age uncertainties into account implies that net retreat rate of the ice margin along the northern shore of Donegal Bay fell within the range 12–24 m a^{-1}, markedly faster than the net rate inferred above (3–5 m a^{-1}) for ice retreat inland from Bloody Foreland to the Derryveagh Mountains. Although subject to the same caveat (that retreat may have been interrupted by one or more ice margin readvances), there is neither morphological nor seismostratigraphic evidence for later readvances of the ice margin as it retreated eastward from the DBM: Ó Cofaigh *et al.* (2018)

noted that the sediment cover east of the moraine comprises undeformed, acoustically-stratified conformable glacimarine sediments overlain by postglacial marine deposits. For comparison, the average net rate calculated by Ó Cofaigh *et al.* (2018) for ice-margin retreat from the shelf edge to the DBM is 11.2–14.0 m a^{-1}, though they considered that this probably incorporated moderately rapid retreat at a minimum rate of 35.7 m a^{-1} from the shelf edge to mid-shelf, followed by much slower oscillatory retreat at a net rate of 5.5 m a^{-1} between the mid-shelf and the DBM.

Wider implications

Collectively, the chronological data reported above indicate a marked contrast in both the timing and rate of net ice margin recession of land-based ice in northern Donegal (~21–17 ka) and retreat of the ice margin in southern Donegal adjacent to Donegal Bay (~17–15 ka). This contrast suggests that the timing of ice-margin retreat was at least partly conditioned by the relationship between ice fed from the Donegal Ice Centre and adjacent ice streams. Northern Donegal lay in an inter-ice-stream location, between the Hebrides/Malin Sea Ice Stream to the north and the Donegal Bay Ice Stream to the south, and here the early (~22–21 ka) decoupling of Donegal ice from the extended Hebrides/Malin Sea Ice Stream appears to have created an ice-free marine embayment along the north coast of Donegal, so that ice flowing from the Donegal Ice Centre was effectively unconstrained, and subsequently retreated gradually in response to a slight net negative mass balance. In contrast, the south coast of Donegal lay near the axis of the Donegal Bay Ice Stream, which was fed not only by ice from the Donegal Ice Centre, but also by ice from the Irish Midlands. Following initial rapid retreat, the oscillating margin of the Donegal Bay Ice Stream retreated slowly from mid-shelf to the DBM (Ó Cofaigh *et al.,* 2018), so that ice cover persisted over south Donegal until ~17 ka, after which it retreated to the footslopes of the Blue Stack Mountains. This contrast in behaviour implies that different dynamics apply to extended marine-based ice streams, which are sensitive to changes in sea level, confinement and bed slope (Smedley *et al.,* 2017; Ó Cofaigh *et al.,* 2018; Small *et al.,* 2018) and land-based ice masses in inter-ice-stream locations, which respond mainly to changes in climate inputs.

Evidence for marked slowing of ice-margin retreat as the shrinking BIIS stabilised at or near the present coastline is not limited to northern Donegal. TCN ages reported by Small *et al.* (2017) for the Sea of the Hebrides to the west of Scotland suggest that termination of ice streaming after ~20.6 ka was succeeded by a ~3000–4000 year interval during which the ice margin experienced oscillatory net retreat of only 50–70 km as it became progressively land-based amongst the islands of the Inner Hebrides. The slowing of ice margin retreat in this area coincides closely with the period of very gradual ice-margin recession in northern Donegal.

The mean exposure age of the samples from low ground (~150 m) at the foot the Blue Stack Mountains (14.8±0.7ka (14.8±1.2 ka)) represents the youngest age for the timing of ice-sheet deglaciation hitherto reported for Ireland and implies that by ~14.7 ka the Donegal Ice Centre had shrunk to a small ice cap or transection complex centred on high ground. An analogous situation occurred in SW Scotland, 240 km to the east, where seven (recalibrated) TCN ages indicate that only fragmented upland remnants of the Galloway Hills Ice Centre remained by ~15.1 ka (Ballantyne *et al.,* 2013a). The Galloway Hills TCN ages are statistically indistinguishable from the Blue Stack ages, and both confirm that almost all ice retreat occurred under stadial conditions prior to ~14.7 ka. In both areas it is unlikely that remnant glacier ice survived subsequent rapid warming, when mean July temperatures inferred from subfossil chironomid assemblages rose rapidly by 5–6°C (Brooks and Birks, 2000; Lang *et al.,* 2010; Watson *et al.,* 2010, Van Asch *et al.,* 2012). A more general implication is that all of Ireland and southern Scotland were probably completely deglaciated early in the Lateglacial Interstade. For the British Isles as a whole, present evidence suggests that remnants of the BIIS survived the interstade (if at all) only in the Highlands of Scotland (Finlayson *et al.* 2011; Ballantyne and Small, 2018).

Conclusions

1. Twenty new TCN ages obtained for sites in northern and southern Donegal complement (and are broadly consistent with) previously-published TCN and radiocarbon ages, and reveal marked contrasts in the timing and rate of deglaciation in northern and southern Donegal.
2. The TCN ages for northern Donegal indicate decoupling of ice fed from the Donegal Ice Centre from the Hebrides/Malin Shelf Ice Stream and associated development of a marine embayment north of Donegal by ~22–21 ka. Conversely, the new TCN ages for south Donegal confirm that ice persisted in much or all Donegal Bay and covered southwest Donegal as late as ~17 ka.
3. In northern Donegal our TCN data imply very gradual ice-margin retreat inland towards mountain source areas at a net rate of 4±1 m a^{-1}; by comparison, the inferred net rate of ice margin retreat from SW Donegal to the foothills of the Blue Stack Mountains near the head of Donegal Bay averaged 18±6 m a^{-1}.
4. We suggest that the above contrast in timing and rate of ice retreat reflect differences in location relative to those of major ice streams. Northern Donegal occupied an inter-ice-stream location, and after early decoupling of Donegal-sourced ice from the Hebrides/Malin Sea Ice Stream the former was unconstrained and retreated mainly in response to changes in climatic inputs. Conversely, southern Donegal lay near to the axis of the Donegal Bay Ice Stream, which occupied (or reoccupied) much of Donegal Bay as late as ~18 ka, delaying deglaciation along the southern coast of Donegal until after ~17 ka.
5. A mean TCN age of ~14.8 ± 0.7 ka (14.8±1.2 ka) obtained for the footslopes of the Blue Stack mountains in southern Donegal is the youngest deglacial age hitherto reported for Ireland, and

implies that shortly before the onset of rapid warming at the beginning of the Lateglacial Interstade (~14.7 ka) the Donegal Ice Centre had shrunk to a small icecap or icefield of very limited extent, and probably disappeared completely during the early part of the interstade. This date also confirms that virtually all of the retreat of the Irish Ice Sheet occurred under stadial conditions prior to the onset of interstadial warming.

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Figures:

Figure 1. Location map of Donegal and parts of Sligo and Mayo with terrestrial legacy ages (TCN and ^{14}C), BRITICE-CHRONO ^{14}C ages for the Donegal Bay Moraine, with core numbers, and sites of new TCN ages reported in this paper. Only those legacy ages of relevance to deglaciation are shown. The first TCN age for each site was calculated using the LLPR, the age in brackets was calculated using CRONUScalc. Ages are mean values of two or more ages for each site except for Glencolumbkille, which is represented, by a single age. Terrestrial ^{14}C ages are minimum ages for deglaciation. Ice divides and generalised ice flow directions are from Greenwood and Clark (2009a). Inset shows location of Donegal and the LGM limit of the BIIS.

Figure 2. **a**: Some of the granite boulders of the moraine at Bloody Foreland; **b**: Part of the spread of glacially-transported granite boulders at Rosguill; **c**: Rosguill boulder ROS-01. The survey pole is divided at intervals of 0.2 m; **d**: Sampled bedrock at Malin Head, site MH-02; **e**: Glencolumbkille boulder GC-02 undergoing sampling of projecting quartz vein; **f**: Blue Stack Mountains boulder BS-01, showing projecting quartz pebbles. Scale bar is divided at intervals of 0.06 m.

Figure 3. Location map of Donegal and parts of Sligo and Mayo with all ages (legacy and new) of relevance to deglaciation. The new TCN ages are given in the same format as the legacy ages in Figure 1. Note that the Malin Head age is a single age and the Glencolumbkille age is the mean of three new ages and the legacy age given in Figure 1. Inferred ice margins (isochrones) are shown as solid lines for ~26-25 ka (lLGM), 22 ka, ~21 ka, ~18 ka, ~16 ka and ~15 ka, and as broken lines for readvance limits at ~19.5 ka (Donegal Bay Moraine) and ~18 ka (Corvish).

Figure 4. Equal-area Gaussian probability distributions representing the uncertainty-weighted means and associated uncertainties for the cosmogenic ^{10}Be exposure ages obtained for samples from the 'coastal' sites on Aran Island (n = 2) and Bloody Foreland (n =7), and the 'inland mountain' sites of Errigal Col (n = 3) and Poisoned Glen (n = 2). These distributions illustrate the overlap in the ages obtained for the two 'coastal' sites and for the two 'inland mountain' sites, and also the temporal interval of ≥4 ka that separates the two sets of ages.

Tables:

Table 1. Terrestrial legacy ages and BRITICE-CHRONO ages pertaining to the deglaciation of Donegal, Donegal Bay and north Mayo.

Table 2. Details of samples for TCN dating from Donegal.

Table 3. TCN (^{10}Be and ^{36}Cl) data and surface exposure ages with total uncertainties at 1σ for the Donegal samples. Analytical uncertainties (1σ) are given in parentheses.

Table 1. Terrestrial legacy ages and BRITICE-CHRONO ages pertaining to the deglaciation of Donegal, Donegal Bay and north Mayo.

Site	^{14}C age±1σ (cal. ka BP[1])	^{10}Be age±1σ (LLPR[2])	^{10}Be age±1σ (CRONUScalc[3])	^{36}Cl ages±1σ[4]	Material and context	Reference
DONEGAL						
Malin Head				25.1±1.1	Glacially-smoothed quartzite bedrock	Bowen *et al.* (2002)
Bloody Foreland				31.0±17.0	Not specified, but granite bedrock or boulder	Bowen *et al.* (2002)
Corvish	17.06±0.18				Marine microfauna: *Elphidium clavatum*	McCabe and Clark (2003)
	19.03±0.19				Marine microfauna: *Elphidium clavatum*	
	18.32±0.18				Marine microfauna: *Ephidium clavatum*	
	19.50±0.50				Marine microfauna: *Elphidium clavatum*	
	18.24±0.13				Marine microfauna: *Elphidium clavatum*	
	20.68±0.16				Marine microfauna: *Elphidium clavatum*	
Bloody Foreland		21.4±1.4 (1.0)	20.7±1.9 (1.0)		Glacially-transported granite boulder	Ballantyne *et al.* (2007)
		18.6±1.2 (0.8)	18.0±1.6 (0.8)		Glacially-transported granite boulder	
Bloody Foreland		18.0±1.8 (1.6)	17.5±2.2 (1.7)		Glacially-transported granite boulder	Clark *et al.* (2009a)
		34.1±3.1 (2.7)	32.5±3.7 (2.7)		Glacially-transported granite boulder	
		22.0±1.8 (1.5)	21.3±2.3 (1.6)		Glacially-transported granite boulder	
		21.4±1.9 (1.7)	20.7±2.3 (1.7)		Glacially-transported granite boulder	
		21.4±2.1 (1.9)	20.7±2.5 (1.9)		Glacially-transported granite boulder	
		23.8±2.2 (1.9)	23.0±2.6 (2.0)		Glacially-transported granite boulder	
		21.9±2.3 (2.0)	21.2±2.7 (2.1)		Glacially-transported granite boulder	
		22.3±2.3 (2.0)	21.6±2.7 (2.1)		Glacially-transported granite boulder	
Mean[5, 6]		***21.8±1.2***	***21.1±1.8***			
Aran Island		21.8±1.2 (0.7)	21.1±1.8 (0.8)		Glacially-transported granite boulder	Cullen (2013)
		21.6±1.2 (0.7)	20.9±1.8 (0.8)		Granite bedrock	
Mean[6]		***21.7±1.1***	***21.0±1.7***			
Glencolumbkille[7]		17.9±0.9 (0.5)	17.4±1.4 (0.5)		Vein quartz in glacially-transported schist boulder	Ballantyne *et al.* (2007)
		19.8±1.0 (0.5)	19.1±1.5 (0.6)		Vein quartz in schist roche moutonnée	

Table 1 continued.

Errigal col		17.4±1.0 (0.6)	17.2±1.5 (0.6)	Glacially-plucked quartzite bedrock	Ballantyne *et al.* (2013)
		18.0±1.0 (0.6)	17.8±1.5 (0.6)	Glacially-plucked quartzite bedrock	
		17.9±1.0 (0.6)	17.7±1.5 (0.6)	Glacially-plucked quartzite bedrock	
Mean[6]		***17.8±0.9***	***17.6±1.4***		
Slieve League		16.9±1.0 (0.7)	16.7±1.4 (0.7)	Quartzite boulder from rockslope-failure debris	Ballantyne *et al.* (2013)
		17.6±1.2 (0.9)	17.4±1.6 (0.9)	Quartzite boulder from rockslope-failure debris	
		16.9±1.1 (0.9)	16.7±1.5 (0.8)	Quartzite boulder from rockslope-failure debris	
Mean[6]		***17.1±0.9***	***16.9±1.4***		
Lough Nadourcan	15.38±0.12			Organic mud, basal lake sediment, bulk sample	Watson *et al.*(2010)
NORTH MAYO					
Fiddauntawnanoneen	20.38±0.31			Marine shell: *Macoma calcarea*	McCabe et al. (1986)
Belderg Pier	19.16±0.21			Marine shell: *Macoma calcarea*	McCabe et al. (1986, 2005)
	19.23±0.26			Marine shell: *Macoma* calcarea	
	19.51±0.29			Marine microfauna: *Elphidium clavatum*	
	19.77±0.35			Marine microfauna*: Elphidium clavatum*	
	19.88±0.33			Marine shell*: Macoma calcarea*	
	19.92±0.34			Marine shell: *Macoma calcarea*	
	22.09±0.28			Marine microfauna: *Quinqueloculina seminulum*	
Donegal Bay	20.24±0.24			Mixed benthic foraminifera	Ó Cofaigh et al. (2018)
	17.92±0.16			Mixed benthic foraminifera	
Ox Mountains		17.0±1.6 (1.4)	17.0±2.0 (1.5)	Vein quartz in glacially-transported gneissic boulder	Clark et al. (2009b)
		15.7±1.6 (1.4)	16.0±2.0 (1.6)	Vein quartz in glacially-transported gneissic boulder	
		16.4±1.5 (1.3)	16.5±1.9 (1.4)	Vein quartz in glacially-transported gneissic boulder	
		16.9±1.5 (1.3	17.0±1.9 (1.4)	Vein quartz in glacially-transported gneissic boulder	
		17.0±1.8 (1.7)	17.1±2.3 (1.8)	Vein quartz in glacially-transported gneissic boulder	
Mean[6]		**16.6±1.0**	***16.7±1.5***		
		19.1±1.8 (1.6)	19.2±2.3 (1.7)	Vein quartz in glacially-transported gneissic boulder	Clark et al. (2009b)
		21.1±1.7 (1.4)	21.0±2.3 (1.6)	Vein quartz in glacially-transported gneissic boulder	

Table 1 continued.

		20.6±2.1 (1.8)	20.7±2.5 (2.0)	Vein quartz in glacially-transported gneissic boulder	

Mean[6]	***20.3±1.3***	***20.3±1.9***

[1]Ages calculated using OxCal 4.2; Marine-13 dataset used for Corvish and Donegal Bay samples (Bronk Ramsey, 2009; Reimer *et al*., 2013).

[2]Ages calculated using the Loch Lomond Production Rate, Lm scaling and 1 mm ka^{-1} surface erosion rate. Uncertainties are total (external) uncertainties. Analytical uncertainties are given in parentheses.

[3]Ages calculated using CRONUScalc, Lm scaling and 1 mm ka^{-1} surface erosion rate. Uncertainties are total (external) uncertainties. Analytical uncertainties are given in parentheses.

[4]Chlorine-36 ages cited as published by original authors.

[5]Mean derives from six consistent values reported by Clark *et al.* (2009a) and one age reported by Ballantyne *et al.* (2007).

[6]Uncertainty-weighted mean.

[7]Site is called Malin Beg in Ballantyne *et al.* (2007).

Table 2. Details of samples for TCN dating from Donegal.

Sample code	Grid reference	Latitude (°N)	Longitude (°W)	Altitude (m OD)	Thickness (cm)	Density (g cm^{-3})	Topographic shielding	Material and context
North Donegal								
Rosguill								
ROS-01	C 0999 4222	55.22690	7.84304	65	4.0	2.66	0.9938	Glacially-transported granite boulder
ROS-02	C 1014 4203	55.22520	7.84062	105	5.0	2.67	0.9997	Glacially-transported granite boulder
ROS-04	C 1015 4191	55.22412	7.84055	105	3.0	2.66	0.9967	Glacially-transported granite boulder
Malin Head								
MH-02	C 3977 5955	55.38112	7.37255	65	5.0	2.59	0.9939	Ice-scoured quartzite bedrock
MH-03	C 3947 5960	55.38156	7.37716	30	3.0	2.65	0.9996	Vein quartz in quartzite bedrock
MH-04	C 3964 5946	55.38033	7.37458	55	2.5	2.58	0.6380	Ice-scoured quartzite bedrock
Poisoned Glen								
PG-01	B 9317 1863	55.01505	8.10675	73	2.0	2.61	0.9962	Glacially-transported granite boulder
PG-04	B 9319 1862	55.01495	8.10653	73	3.0	2.62	0.9891	Glacially-transported granite boulder
PG-05	B 9324 1862	55.01498	8.10572	75	2.5	2.56	0.9969	Glacially-transported granite boulder
South Donegal								
Glencolumbkille								
GCS-01	G 5100 8474	54.70850	8.76100	25	1.5	2.65	0.9974	Vein quartz in glacially-transported schist boulder
GCS-02	G 5107 8468	54.70790	8.75990	40	2.0	2.65	0.9983	Vein quartz in glacially-transported schist boulder
GCS-03	G 5114 8464	54.70760	8.75890	35	1.0	2.65	0.9982	Vein quartz in glacially-transported schist boulder

Table 2 continued.

Kilcar								
KC-01	G 6063 7468	54.61870	8.60960	50	5.0	3.05	0.9980	Glacially-transported dolerite boulder
KC-02	G 6063 7468	54.61870	8.60960	50	4.0	3.04	0.9987	Glacially-transported dolerite boulder
KC-03	G 6063 7468	54.61870	8.60960	50	3.5	3.04	0.9665	Glacially-transported dolerite boulder
KC-04	G 6066 7470	54.61890	8.60900	45	6.0	3.03	0.9838	Glacially-transported dolerite boulder
Blue Stacks								
BS-01	G 9276 8608	54.72280	8.11320	150	1.0	2.65	0.9988	Quartz pebbles in glacially-transported conglomerate boulder
BS-02	G 9270 8604	54.72250	8.11400	148	3.5	2.40	0.9967	Glacially-transported comglomerate sandstone boulder
BS-03	G 9254 8611	54.72310	8.11650	150	2.0	2.65	0.9993	Quartz pebbles in glacially-transported conglomerate boulder
BS-04	G 9242 8620	54.72390	8.11840	163	5.0	2.26	0.9993	Glacially-transported conglomerate sandstone boulder

Table 3. Cosmogenic (^{10}Be and ^{36}Cl) data and surface exposure ages with total uncertainties at 1σ for the Donegal samples. Analytical uncertainties (1σ) are given in parentheses.

Sample code	AMS ID	^{10}Be (10^4 atoms g^{-1})	Blank ^{10}Be (10^4 atoms)	^{36}Cl (10^4 atoms g^{-1})	Blank ^{36}Cl (10^4 atoms)	^{10}Be Exposure Age[1] (LLPR)	^{10}Be Exposure Age[2] (CRONUScalc)	^{36}Cl Exposure Age[3] (CRONUScalc)
North Donegal								
Rosguill								
ROS-01	b10320	7.828±0.253	0.609±0.102			18.7±1.1 (0.7)	18.4±1.6 (0.7)	
ROS-02	b10322	9.257±0.418	0.609±0.102			21.4±1.4 (1.0)	21.0±1.9 (1.0)	
ROS-04	b10323	8.331±0.254	0.609±0.102			18.9±1.1 (0.6)	18.7±1.6 (0.6)	
Mean[4, 5]						***18.8±0.9***	***18.6±1.5***	
Malin Head								
MH-02	b10324	9.602±0.363	0.609±0.102			23.3±1.4 (1.0)	23.0±2.0 (0.9)	
MH-03	b10286	8.433±0.272	0.609±0.102			20.7±1.2 (0.7)	20.2±1.7 (0.7)	
MH-04	b10426	6.881±0.472	0.827±0.142			25.5±1.7 (1.2)	25.2±2.3 (1.2)	
Poisoned Glen								
PG-01	b10628	7.413±0.328	0.785±0.108			17.2±1.1 (0.8)	16.7±1.5 (0.7)	
PG-04	b10629	6.876±0.315	0.785±0.108			16.2±1.0 (0.8)	15.7±1.5 (0.7)	
PG-05	b10630	5.605±0.276	0.785±0.108			13.0±0.9 (0.6)	12.6±1.2 (0.6)	
Mean[4, 6]						***16.7±0.9***	***16.2±1.4***	
South Donegal								
Glencolumbkille								
GCS-02	b8570	6.672±0.291	0.894±0.159			16.3±1.0 (0.7)	16.0±1.4 (0.7)	
GCS-03	b8572	7.192±0.306	0.894±0.159			17.3±1.1 (0.7)	17.0±1.5 (0.7)	
GCS-04	b8573	6.873±0.293	0.894±0.159			16.5±1.0 (0.7)	16.2±1.5 (0.7)	

Table 3 continued.

Mean[4]						***16.7±0.8***	***16.4±1.4***	
Mean[4, 7]						***17.2±0.8***	***16.8±1.3***	
Kilcar								
KC-01	c4058			11.767±0.451	6.872±1.722			18.1±1.7 (0.7)
KC-02	c4059			12.378±0.598	6.872±1.722			37.2±6.2 (2.1)
KC-03	c4060			11.796±0.473	6.872±1.722			42.0±6.0 (1.9)
KC-04	c4061			13.951±0.558	6.872±1.722			37.1±5.3 (1.7)
Blue Stacks								
BS-01	b9962	6.163±0.331	1.683±0.177			14.6±0.9 (0.6)	14.5±1.3 (0.6)	
BS-02	b8568	7.097±0.301	0.894±0.159			15.6±0.9 (0.7)	15.6±1.4 (0.6)	
BS-03	b8569	6.984±0.303	0.894±0.159			14.9±0.9 (0.6)	14.8±1.3 (0.6)	
BS-04	b10285	6.729±0.206	0.814±0.103			14.4±0.8 (0.5)	14.5±1.3 (0.5)	
Mean[4]						***14.8±0.7***	***14.8±1.2***	

[1]Exposure age based on Loch Lomond Production Rate (LLPR), time-dependent Lm scaling (Lal, 1991; Stone, 2000) and assuming 1 mm ka^{-1} erosion.

[2]Exposure age derived from CRONUScalc v2.0 with Lm scaling and assuming 1 mm ka^{-1} erosion.

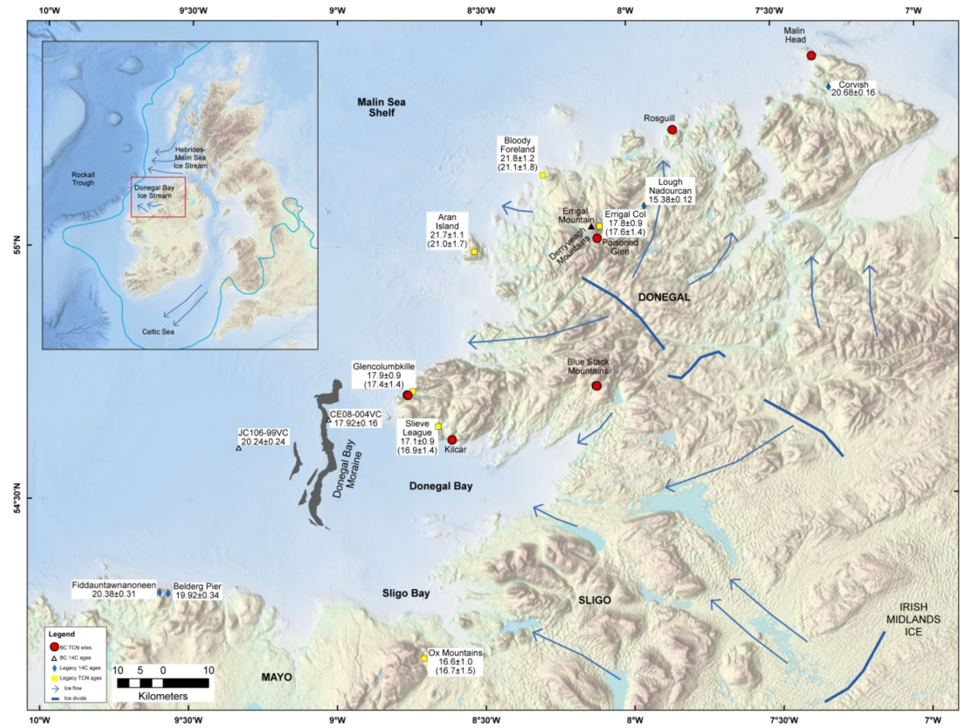
[3]Exposure age based on CRONUScalc v2.0 with Lm scaling.

[4]Uncertainty-weighted mean value.

[5]Mean value based on ROS-01 and -04 only.

[6]Mean value based on PG-01 and-04 only.

[7]Mean value includes an additional sample age reported by Ballantyne *et al*. (2007).



10°W
9°30'W
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Malin Head
Corvish 20.68±0.16
Malin Sea Shelf
Rosguill
Bloody Foreland 21.8±1.2 (21.1±1.8)
Lough Nadourcan 15.38±0.12
Errigal Mountain
Errigal Col 17.8±0.9 (17.6±1.4)
Aran Island 21.7±1.1 (21.0±1.7)
Derryveagh Mountains
Poisoned Glen
DONEGAL
Glencolumbkille 17.9±0.9 (17.4±1.4)
Blue Stack Mountains
CE08-004VC 17.92±0.16
JC106-99VC 20.24±0.24
Slieve League 17.1±0.9 (16.9±1.4)
Kilcar
Donegal Bay Moraine
Donegal Bay
Fiddauntawnanoneen 20.38±0.31
Belderg Pier 19.92±0.34
Sligo Bay
SLIGO
IRISH MIDLANDS ICE
Ox Mountains 16.6±1.0 (16.7±1.5)
MAYO
Legend
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Kilometers
Rockall Trough
Hebrides-Malin Sea Ice Stream
Donegal Bay Ice Stream
Celtic Sea

Figure 1

Figure 2

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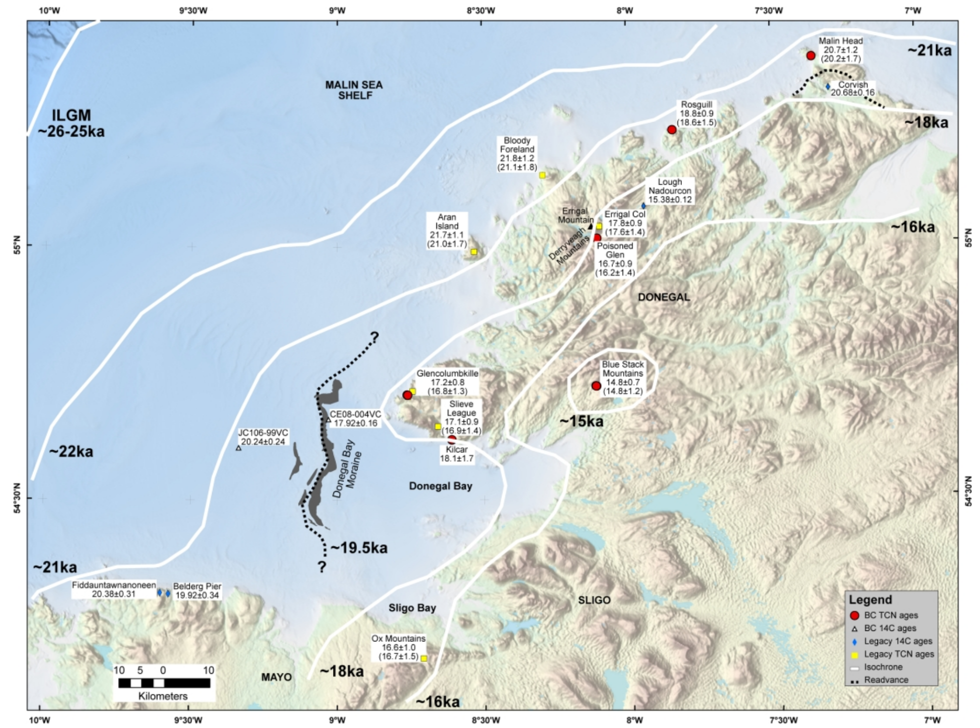
MALIN SEA SHELF
ILGM
~26-25ka
~22ka
~21ka
~19.5ka
~18ka
~16ka
~15ka
Bloody Foreland 21.8±1.2 (21.1±1.8)
Aran Island 21.7±1.1 (21.0±1.7)
Rosguill 18.8±0.9 (18.6±1.5)
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DONEGAL
Blue Stack Mountains 14.8±0.7 (14.8±1.2)
Glencolumbkille 17.2±0.8 (16.8±1.3)
Slieve League 17.1±0.9 (16.9±1.4)
Kilcar 18.1±1.7
CE08-004VC 17.92±0.16
JC106-99VC 20.24±0.24
Donegal Bay Moraine
Donegal Bay
Fiddauntawnanoneen 20.38±0.31
Belderg Pier 19.92±0.34
Sligo Bay
Ox Mountains 16.6±1.0 (16.7±1.5)
MAYO
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Kilometers
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55°N
54°30'N

Figure 3

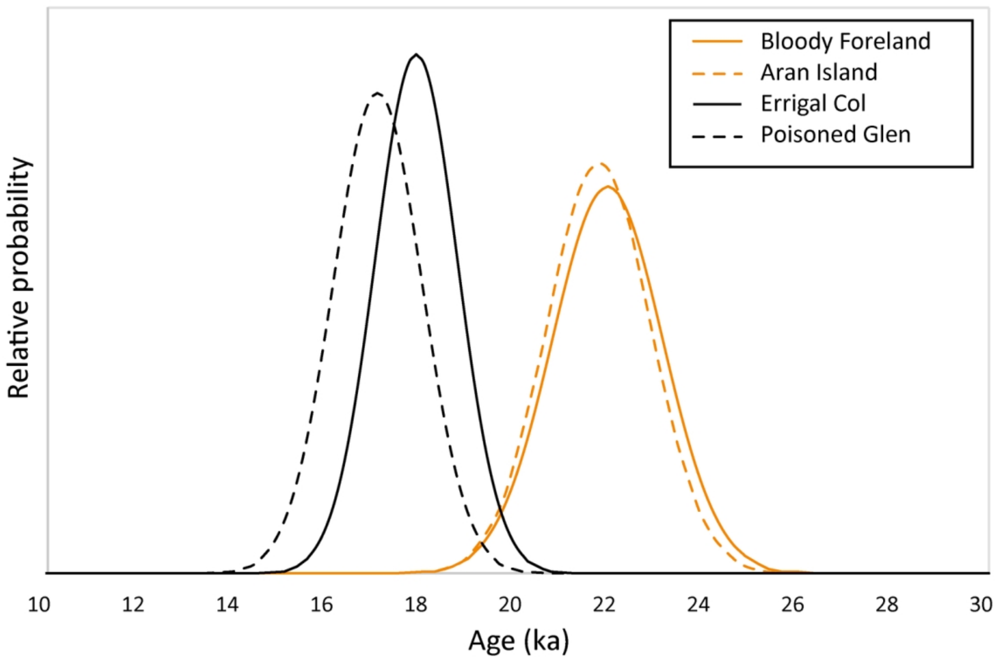

Figure 4

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